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USE OF FLY ASH FOR ROAD CONSTRUCTION WITH SPECIAL REFERENCE TO BASE AND SUBBASE COURSES

Report No 87-3-K

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ABSTRACT

The purpose of this report is to discuss the use of fly ash for road construction, and the main effort is concentrated on the use of the ash as a base or subbase course material. The study examines present practices in Ontario, and analyses the effect which chemical additives, such as lime and or cement have on the physical characteristics of the aggregate material. Case records on the use of fly ash with additives as it applies to road base courses are examined and the knowledge gained from these past experiences are applied to the condition inherent to southern Ontario.

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TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1
2.0	GENERAL USE OF FLY ASH IN HIGHWAY AND ROAD CONSTRUCTION	1
2.1	Embankments	2
2.2	Surface Course	3
2.3	Subgrade Stabilization	4
2.4	Base Courses and Subbase Courses	8
3.0	TESTING PROCEDURES	9
3.1	Strength Testing	10
3.2	Durability Testing	11
3.3	Quality Control Testing	11
3.4	Field Monitoring	12
4.0	CASE HISTORIES	12
4.1	Harrison Power Station, West Virginia	13
4.2	Ash Haul Road, Pennsylvania	15
4.3	Service Road, Pennsylvania	17
4.4	Airport Runwayk, Newark	19
4.5	Warehouse Access Road, Ontario	21
5.0	TECHNICAL FEASIBILITY IN SOUTHERN ONTARIO	23
6.0	SUMMARY	25
REFERENCES		28
TABLES		29
FIGURES		34
DISTRIBUTION		last page

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USE OF FLY ASH FOR ROAD CONSTRUCTION WITH SPECIAL REFERENCE TO BASE AND SUBBASE COURSES

1.0 INTRODUCTION

The objective of this project is to examine the use of fly ash as a highway and road construction material. In particular, the study is concentrated on the use of fly ash, stabilized either by lime and or cement, for road base or subbase courses. Initially, the report will discuss in general the use of fly ash in highway and road construction. Further, a more detailed discussion on the use of lime/cement stabilized ash road base and subbase courses will be presented. Case histories on the successful uses of stabilized ash road base courses will be discussed. It is concluded that the knowledge gained from these experiences can be applied to the conditions in Southern Ontario.

2.0 GENERAL USE OF FLY ASH IN HIGHWAY & ROAD CONSTRUCTION

Fly ash can be utilized effectively in many aspects of highway or road structures. The use of this by-product resource in the following engineering applications will be described briefly/1/.

1. embankments
2. surface course
3. subgrade modification
4. base courses and subbase courses

2.1 Embankments

Fly ash has been successfully used worldwide as a borrow material for the construction of roadway embankments. This began in the late 1950's in Great Britain with the construction of a number of trial sections to convince local engineers of the suitability and advantages to be gained when utilizing fly ash.

Two primary factors which have led to the acceptance of this alternative are the light weight of fly ash which eliminates the need for time consuming stage construction/2/ as well as the economic considerations which can be realized. Full advantage of the light unit weight of fly ash can be utilized when dealing with fill operations on weaker subsoils. The dry unit weight of fly ash is approximately 75% of that of conventional granular materials, a fact which often eliminates the concerns of excessive settlement and ultimate failure of the underlying strata. Obviously a scheme could be developed whereby the weak stratum could be improved by conventional surcharging, vibrofloatation of removal. However depending on the local availability of fly ash to the site, it becomes apparent that savings in both time of construction and money are extremely likely/1/.

When dealing with roadway embankment construction, concerns are raised as to the material's strength. Laboratory and field tests have shown that fly ash exhibits strengths equal to those for more conventionally-used materials and in fact often have shear strengths which exceed those found in many soils due to the self hardening process. These shear strengths can be realized in relatively short periods of time offering further economic incentive over other embankment materials.

Concerns about possible frost susceptibility problems of the fine-grained fly ash have repeatedly been raised. This problem has been solved effectively by placing fly ash only below the depth of normal frost penetration (approx. 1.2 m) or by lightly stabilizing any fine-grained material which lies within this zone. Other concerns with respect to embankment construction have also been solved using proper design and good construction techniques. These include: 1) dusting of the dry light weight fine particles which is controlled by regulation of the ash moisture content, 2) erosion of slopes which can be solved by placing a thin layer of soil cover and seeding and 3) the danger of chemical leaching which can be minimized through proper compaction, adequate drainage and proper design.

In Ontario, a major cloverleaf interchange of Highway 402 in Sarnia was constructed using coal ash and monitored for settlement, frost penetration, frost heave and ground water

chemistry in 1981. What follows is the summary of an article by Chris Cragg, "Fly Ash Speeds Bridge Construction" where the author indicates the success which this project enjoyed/2/.

"Monitoring of a major fly ash embankment at Sarnia, Ontario showed good frost and settlement performance. Frost heave was minimal despite frost penetration up to 1.03 m. Settlement of the embankment coal ash fill was negligible. Settlement of the compressible soil underlying the embankment was less than calculated but somewhat higher than that was expected based on experience. Substantially larger settlements would have occurred if earth fill had been used instead of the low density fly ash fill. By using fly ash fill, time consuming staged construction was avoided at this site. In this respect, fly ash speeded the bridge construction.

Fly ash is recommended for use in future structural fills based on its good performance at this site".

2.2 Surface Course

Fly ash can be used as a surface course in various different manners. These include as a filler in bituminous concrete or as a constituent of Portland cement (OECD Road Research Group, 1977)/3/.

Bituminous paving mixtures have been designed to include mineral filler since about 1890. Filler describes both the finest mineral element added to a bituminous mixture and the fraction of the mineral aggregate in the mixture which passes the 75 μm sieve.

Comparisons between fly ash and natural fillers have found that the chemical compositions does not differ materially and that as a result, fly ash is suitable for bitumen aggregate mixtures. A further feature which makes this a successful utilization alternative, is the particle size distribution of fly ash which effectively fills voids in the mixture. It should be noted that the carbon content of the ash influences the stability of the finished product and that upon investigation, a carbon content of 9% yielded maximum stability results/3/. Ontario Hydro fly ashes generally have carbon contents in the 8% to 10% range and as a result are suitable for this utilization alternative.

The use of fly ash as a constituent of Portland cement has been well documented. For the purposes of this report, it suffices to say that fly ash has both beneficial and undesirable effects when used in concrete. Some of the benefits which can be realized are: reduced water requirement; enhanced workability; increased strength at given cement content; improved uniformity of strength development and reduced permeability. The

undesirable effects are primarily related to quality control due to variables experienced in the chemical and physical properties of fly ash.

2.3 Subgrade Stabilization

This subsection deals with the possibility of stabilizing the subgrade, the ground surface which acts as a foundation for a pavement, embankment or other structure. Soil stabilization generally refers to the physical and/or chemical methods used to improve natural soils or soil aggregates for use in some engineering application/1/. For this purpose, fly ash has been effectively utilized and has been shown to reduce plasticity, increase shear strength and improve the workability of weak soils/4/. Economically speaking, savings have resulted due to reduced pavement design thicknesses and saved construction time of roads being established on particularly wet or unstable subgrades.

Past experience with chemical stabilizers has shown that the addition of cement, lime or lime-fly ash mixtures has significantly improved soils in the following manner: 1) By altering the soils inherent properties such as decreasing its plasticity index and improving its drainage characteristics; and 2) by increasing both the strength and durability of the soil due to a cementation process which takes place. In the lime-fly ash mixtures, this process takes place due to the reactions which occur between the lime and the pozzolanic fly ash producing calcium silicates and aluminates.

Extensive work has been undertaken on the stabilization of soils using Class C fly ash (ie higher CaO content ash) alone with promising results. This type of fly ash is normally produced from lignite or sub-bituminous coal and has pozzolanic and cementitious properties which account for its success. However, in Ontario, the more common fly ash produced is Class F fly ash which results from the burning of anthracite or bituminous coal and has only pozzolanic properties. As a result, more success has been achieved when chemical stabilizers, such as lime and cement, have been added to the fly ash-soil mixture producing increases in both strength and durability characteristics of weak subgrades.

In general, fine-grained soils provide a relatively weak subgrade with poor strength and durability characteristics. Other problems associated with fine-grained soils, are specific to Ontario and other northern climates in their frost susceptibility and shrink-swell characteristics. The results of adding lime and fly ash to clayey soils is that they become more frost resistant due to a reduction in volumetric shrinkage and by absorbing and chemically binding moisture.

There are a number of factors which influence the success achieved with lime-fly ash-soil and cement-fly ash-soil mixtures. These include:

- soil type
- fly ash type
- lime type/cement type
- proportion of stabilizers to soil
- ratio of lime to fly ash/cement to fly ash
- dry density and moisture content of compacted mixture
- age of mixture
- temperature

Each of these factors will be discussed briefly below and more detail on each point can be found in section 6 of Dry Ash Utilization Manual, prepared by GAI Consultants Inc/4/.

Soil Type

Due to the mineralogy of clays made up of illite, chlorite, vermiculite or koalinite, it has been found that the addition of fly ash to the lime improved the performance due to the pozzolanic tendencies in the minerals. A great deal of variation exists as to the optimum ratio of lime to fly ash in terms of performance. Mixtures become a problem of choosing the most economical combination which can be achieved and yet meet the specific requirement of the job. Ranges of 1:9 to 1:1 (lime:fly ash) have been effectively used.

In granular soil projects, where an excessive rain fall has produced unworkable subgrade conditions, the addition of lime and fly ash has successfully absorbed excess moisture from the soil.

Fly Ash Type

Tests which determine the physical and chemical properties of the fly ash must be performed and give some indication of how well the mixture of lime-fly ash-soil will behave. The most important of these are:

Blaine Fineness - the finer fly ash particles the greater the pozzolanic reaction.

Carbon Content - high carbon content inhibits the pozzolanic reactivity.

Calcium Oxide (CaO) Content - reacts with the siliceous and aluminous compounds in the fly ash to produce cementation.

Lime Type

There are two classes of lime which are used in soil stabilization:

1) Hydrated Lime [$Ca(OH)_3$]

2) Quicklime [CaO]

One disadvantage of quicklime is that it is highly caustic. Hydrated lime is commercially available and the properties are summarized in Table 1.

Cement Type

Most cement used in cement-fly ash-soil stabilization projects is a commercially available portland cement. The properties of this cement are summarized in Table 2.

Proportion of Stabilizer to Soil

For a given lime to fly ash ratio the compressive strength of the mixture increases as the total amount of stabilizer is increased (see Figure 1) resulting in an economic decision having to be made as to the stabilizer percentage. The same phenomena occurs in cement-fly ash-soil mixtures.

Ratio of Stabilizer to Fly Ash

As discussed earlier, mix proportions are seldom critical for a given soil and a number of mixes could be used which would result in approximately the same mixture performance.

Dry Density and Moisture Contents

The compressive strength of the stabilized mixtures increases with increased density to a point near maximum dry density as determined in a Standard Proctor Test. The moisture content for maximum density is used in the laboratory testing program for determining mix design.

If it is anticipated that field compaction in excess of Standard Proctor can be economically obtained, the higher density obtained in the Modified Proctor test may be more suitable for design and construction purposes.

Age of Mixture

This is one factor in which cement stabilization and lime stabilization have vastly different initial results but with time develop approximately the same characteristics.

This is because the strength development in lime-fly ash-soil mixtures occurs at a slower rate than that for cement. Durability is also a function of the curing period of the mixture. This results in slightly different laboratory and field testing procedures. The major difference is the curing time before compressive strength tests are performed. For cement-soil mixtures, this is done after seven days and 28 days while for lime-soil mixtures, the testing is performed after 28 days and 45 days.

Due to Ontario's climate, this has significant importance during construction. Due to the slower strength development of the lime mixture, it is recommended that construction take place only during the warmer months and at least one month before the anticipated first frost/4/. It must be noted that accelerators can be added to the lime-mixtures to increase the rate of strength development. Examples include sodium carbonate in small quantities and portland cement in low percentages.

Temperature

It is a well documented fact that in any pozzolanic reaction the rate is more rapid at higher temperatures and ceases at temperatures below 4°C. So the same can be said for the lime-fly ash and cement-fly ash mixtures due to the pozzolanic activity which occurs. It should be noted that warmer temperatures reactivate the pozzolanic reaction which then proceeds until the chemical compounds participating in the reaction are depleted.

As a result of the influence of temperature on the reaction, specific curing temperatures for unconfined compression testing have been formulated and set at 21° ± 2°C.

What has been presented above is a brief overview of the use of chemical stabilizers in soils to be used as a subgrade. When dealing with high quality sand or gravels as the natural soil, research and case examples have shown that it is possible to consider the stabilized subgrade as subbase or base course and

subsequently reduce the pavement design thickness. As the focus of this report deals with fly ash in base course material, it was determined appropriate to include some of the more pertinent details of subgrade stabilization. The remainder of the report will deal specifically with the use of fly ash in base course materials and will consist of a brief overview of the state-of-the-art followed by case histories.

2.4 Base Courses and Subbase Courses

This subsection describes the use of fly ash as the base course or subbase course component of roadway pavement. The use of stabilizers such as lime and cement plus fly ash and aggregate have been successfully used as pavement base course for years. The mixture of lime-fly ash-aggregate is known as LFA. Substitution of portland cement for all or part of the lime in the mixture is known as CFA or LCFA.

As opposed to using aggregate it is possible to use cement or lime stabilized fly ash alone as a subbase or base course. In this case fly ash acts both as a pozzolan and an aggregate with the pozzolanic reaction between the fly ash and the stabilizer continuing to produce increases in strength, paralleled by an increase in durability of the base or subbase course.

As the use of LFA mixtures is fairly common in both the northern United States and Canada, the studies will be concentrated on stabilized fly ash mixtures (no aggregate). Only a brief discussion of LFA is presented as below.

A wide range of aggregate types and gradations have been used successfully including sands, gravels, crushed stones and several types of slag. Some of the requirements of LFA or CFA mixtures is that they be mechanically stable under compaction equipment and that field compaction to a high density be economically possible. The aggregate itself should be made up of hard, durable particles which are free of soft or disintegrated pieces as well as deleterious organic or chemical substances/5/.

Gradation of the aggregate is of vital importance to the final success with aggregates containing greater fines contents resulting in greater durability while coarse aggregate gradations have yielded more mechanically stable bases.

When dealing with stabilized fly ash base courses without aggregate, we are dealing with a subject which has had far less exposure in North America than LFA base course. However, European experience under similar climatic conditions has demonstrated that this is, in fact, a viable base course

material. In southern Ontario, further attractions to this alternative exist due to the availability of fly ash and the often prohibiting cost of suitable aggregate. This alternative is preferable to that discussed in Section 2.3 of stabilized subgrade soils in that a uniform quality material can be attained.

It should be noted that although many of the Class F fly ashes possess self-hardening properties, their rate of strength development is not adequate for pavement use without chemical additives. A further reason for incorporating lime or fly ash into the mixture is due to the requirement for both load bearing capacity and frost resistance due to the climate of southern Ontario.

The basic design approach for establishing a stabilized fly ash base course put forth by GAI Consultants Inc. in their publication: Dry Ash Utilization Manual/4/ is extremely comprehensive and is highlighted below:

- Determine the method of stabilization. Lime, cement and the self-hardening properties of the ash or a combination of these factors may be used.
- Identify the source or sources of ash to be used.
- Develop mix design for the base course.
- Determine the thickness of the base course and wear surface.
- Determine construction procedures and quality control methods.

The steps put forward are self-explanatory and need not be discussed in more detail in this report. However, the reader is referred to the aforementioned publication for reference purposes. Once an adequate design mix has been developed and can be readily and economically produced for field use, the greatest concern becomes the construction details.

3.0 TESTING PROCEDURES

The key to achieving good results when applying fly ash mixes as road and highway base and subbase courses is to have a comprehensive testing program. Based on the results of these tests, confidence can be gained and support for the use of coal by-products in this engineering application will be realized.

Two of the most basic areas of testing of base course material are: 1) strength and 2) durability. Based on trial specimens results, optimum conditions and mix designs can be developed which will limit settlement, frost susceptibility and heave as well as environmental problems.

3.1 Strength Testing

A number of trial mixes must be formed by altering the proportions of lime/cement to fly ash. This will enable an optimum mix design to be utilized based on the following test procedures.

A. Compact each of the mixtures in accordance with ASTM D-698-70 in order to determine the maximum dry density and the corresponding moisture content. The selection of representative samples of fly ash is of vital importance to the results to be determined. If samples are being retrieved from dry storage, they should be obtained over a long period of time. For stockpiles and lagoons, samples should be taken from different locations. After suitable samples have been retrieved, tests to determine the reactivity of the fly ash should be performed such as Blaine Fineness (ASTM C311-68), Loss-on-Ignition (ASTM C311-68) and the Calcium Oxide (CaO) content.

Case (i) - Addition of Cement

Unconfined compressive strength tests must be performed on appropriately dimensioned test cylinders for each trial mix. The tests must be performed after seven days of curing at a constant temperature of 21±2°C under a relative humidity of 100%. Due to often unreliable results it is recommended that more than one cylinder of a specific trial mix be tested, averaging the results.

Case (ii) - Addition of Lime

Due to the fact that lime-fly ash mixtures have a lower rate of strength gain than for cement-fly ash mixtures, instead of performing the 7-day compression test, it is required to test the samples after 28 days.

C. It is at this stage that some trial mixes may be discarded or revised. In the case of cement addition, if the cylinders fail to reproduce a seven-day unconfined compressive strength of 2760-3100 kPa, then they must be redesigned. In the case of lime addition, a minimum unconfined compression strength after 28 days of 3790-4135 kPa is required.

If the samples have strengths which exceed the specifications, then the mix design becomes a question of economics whereby savings on the more costly lime or cement may occur with an altering of the mix design.

D. Further unconfined compression testing must be performed on satisfactory trial mixes after step C above.

Case (i) - Addition of Cement

Tests conducted after seven days are repeated again after 28 days to determine the mixes' strength gain with time.

Case (ii) - Addition of Lime

Tests conducted after 28 days are repeated again after 45 days of curing.

3.2 Durability Testing

Due to the harsh climatic conditions of Ontario and the resulting severe field conditions, a freeze-thaw durability test (ASTM D560) must be performed on trial mixes which satisfy the compressive strength requirements previously specified. Details of the procedure used in the freeze-thaw test can be found in: Demsey, F.J., and Thompson, M.R., "A Vacuum Saturation Method for Predicting the Freeze-Thaw Durability of Stabilized Materials." Record No 442, Highway Research Board, 1973.

3.3 Quality Control Testing

Once a satisfactory mix has been selected, the sources for the materials chosen and an adequate pavement thickness designed, it is vital for the subsequent success of the project to develop an intensive field testing and monitoring program.

Verification of laboratory test results can be achieved by constructing a test strip to determine if specified compaction requirements are obtainable.

Due to the variation in fly ash properties, such as carbon content and free lime content, quality control of the construction process is required. The variations in the properties is partly due to the time of year at which the fly ash is produced. The carbon content is typically much lower in Ontario ashes in the winter when the generating stations are functioning at maximum capacity tending to be more efficient than during the summer months when at times they may be shut down. As was discussed earlier the carbon content is proportional to the efficiency of the boiler and is the constituent responsible for low strength in the mixture.

Adequate quality control tests are as follows/1/:

1. Moisture Density Relationship (AASHTO T 134-74)

2. Moisture Content (ASTM D 2216-71)

3. i) Cement Content of Freshly Mixed Base Course Material (AASHTO D2901-70)

   ii) Lime Content of Freshly Mixed Base Course Material (AASHTO T 232-70)

4. In-place Density

5. Unconfined Compressive Strength (AASHTO T 22-74)

6. Depth of Mixing for Mix-in-Place Methods (visual).

3.4 Field Monitoring

Ontario Hydro has developed techniques which can be effectively used to monitor in-place conditions of the fly ash mixture base course or subbase course material. These include frost penetration and frost heave, settlement and ground water chemistry monitoring devices which are discussed in an article by Chris Cragg, "Fly Ash Speeds Bridge Construction"/2/. Although this was applied to an embankment fill, it is anticipated that the principles utilized would apply to the use of fly ash as a base course for highway and road construction.

With respect to the environmental monitoring program discussed in the above-mentioned article, it is apparent that in the base course application, the procedures would be much less involved than for the fill application. A perforated PVC pipe network could be installed beneath the base or subbase to allow leachate to enter, which can subsequently be analyzed/1/.

4.0 CASE HISTORIES

In any project of this sort, there remains many questions as to the success which may result. These questions are best answered with a study of case histories and subsequent discussions on effective practices to be followed in the use of fly ash as a base or subbase course material. A few case histories from the northern United States were chosen owing to the similar requirements for strength and durability which their stabilized bases must possess as well as the success achieved in these regions. A case study from Toronto, Ontario also follows.

4.1 Harrison Power Station, West Virginia

In 1975 a parking lot pavement of approximately 10,000 square yards (8400 m^2) was constructed at the Harrison Power Station in Haywood, West Virginia. The pavement design was comprised of a cement-stabilized Class F fly ash base course and a bituminous wear surface/4/.

The mix design chosen for the base course was as follows:

Ingredient	Mix Proportions	Total Quality
Fly Ash	83 pcf (37.5 kg) of mix	3800 tons
Cement	10 pcf (4.5 kg) of mix	360 tons
Water	18 pcf (7.6 kg)	

Due to the close proximity of the construction materials, mixing was accomplished at an on-site batch plant consisting of hoppers, conveyors and a Barber-Greene pug mill which was able to pug up to 200 tons per hour even though the crew was inexperienced in the use of fly ash.

Prior to spreading the mixed base course, the subgrade was proof rolled after which spreading began with the use of an asphalt paver. Compaction with a pneumatic-tire roller followed immediately and proved inadequate to allow the roller to operate efficiently.

Consequently, the base course was tailgated directly from the dump trucks and spread to a loose lift thickness of twelve inches (30 cm) using a tracked D-9 dozer. Compaction with a self propelled vibratory roller (8 tons), fine grading with a road grader and further compaction with a vibratory roller reduced the loose lift thickness down to eight inches (20 cm) of compacted base course. Testing with a nuclear densometer revealed that an average in-place density of 98.5% of a maximum dry density of 92.5 pf (1480 kg/m^3) at an optimum water content of 15% had been achieved. It was felt that a great deal of the compaction was achieved due to the use of the dozer. However, it would have been preferable to have used a jersey box spreader, if one had been available, to better control the loose lift thickness. An average rate of spreading and compacting of 150 tons per hour was easily attainable.

Once spread and compacted, the base course was kept moist during the day with a water truck and sealed with an RS-1 emulsified asphalt seal coat at a rate of 0.30 gallons per square yard.

After a curing period of two weeks, a three inch bituminous wear surface was constructed over the base course, since which the parking lot has been functional and satisfactory.

Testing Results:

Age of Base Course Core (days)	Average Unconfined Compressive Strength psi (kPa)
7	566 (3600)
90	869 (5987)
180	872 (6007)
360	925 (6363)

As is seen, the compressive strength has increased for approximately one year although the ambient air temperature had dropped below freezing several times during the first 90 days after completion. It must be noted that the strength gain was satisfactory as construction began late in the season (September 1975).

In terms of durability, visual inspections at the time of obtaining core samples revealed no indication of pavement failure, or shrinkage cracks. Approximately nine years after construction, a single crack was observed running across the width of the parking lot.

Applicability to Southern Ontario

What has been demonstrated above is the enormous success which can be achieved by utilizing stabilized fly ash base course. It is expected that this success would be possible in southern Ontario if the construction mix was altered to include more stabilizer (cement) due to our more severe winter season. Complete laboratory testing would have to be conducted to arrive at a suitable mixture. It is also recommended that construction in Ontario begin earlier in the season to allow adequate strength gain to take place before the first frost. As we are dealing with similar class F fly ash produced by Ontario Hydro generating stations, it is expected that similar strength and durability properties can be readily established. It was also demonstrated in the above example that cement-stabilized fly ash pavements could be constructed by standard paving crews using conventional equipment which has obvious advantages in terms of production and economy.

4.2 Ash Haul Road, Pennsylvania

During the summer of 1983, the Pennsylvania Electric Company constructed a new ash haul road at its Keystone Steam Electric Generating Station in Shelock, Pennsylvania. Due to increasing stringent environmental regulations of the disposal of over two and one-half million tons of fly ash produced yearly here, alternate disposal projects were formulated/6/.

The largest disposal project for Pennsylvania Electric Company was the use of a lime/fly ash/aggregate base course (LFA) to construct a one and one-half mile long ash haul road at the Keystone Station. The aggregate which was used is summarized in Table 3.

Test results of trial mixtures revealed that the maximum dry density was achieved with a 15% fly ash content (Table 4). This information was used to establish samples composed of 15% by weight of finer (lime and fly ash) and 85% aggregate. Lime contents of 3, 3.5 and 4% were then tested after curing for seven days at 100°F. The results are shown in Table 5.

Durability tests were performed and results of both the vacuum saturation test and a freeze-thaw test revealed that the material was satisfactory and should perform well under freeze-thaw conditions.

Central Plant mixing was used to blend the LFA mixture. The plant blended mix was delivered to the prepared subgrade in open bed trucks except where long haul distances posed possible dusting problems. In these cases, tarpaulins were used to prevent loss of moisture from the mixture.

Spreading was done using equipment with automatic grade control because better uniformity of depth with a minimum of manipulation and segregation was possible. Loose lift thicknesses were 15 to 30% greater than the maximum lift of material after compaction of eight inches. At Keystone, two lifts were applied and the time between placing lifts was kept at a minimum so that the lower layer did not set up before the second layer was placed.

Compaction was achieved using conventional pneumatic tire rollers and vibratory rollers which proved effective in attaining a high relative in-place density which has proven to be directly proportional to strength development. Final rolling of the grade was accomplished with a steel wheel roller. Of vital importance to the success of any compaction attempt using fly ash is to complete compaction operations shortly after spreading to prevent set up.

In this case, such operations were attempted to be completed within three hours of mixing.

A seal coat of emulsified asphalt was spread at a rate of 0.10 to 0.15 gallons per square yard to prevent loss of moisture and was applied to more than 24 hours after completion of the finishing operations.

What this project successfully demonstrated was that substantial savings can result with the substitution of LFA base course for conventional paving designs (approximately $160,000). As well, an environmentally safe method of disposing of 20,000 tons of fly ash was developed.

Further advantages are that the LFA base course will continually develop strength over a long period of time and that no specialized construction equipment was required in the construction process.

Some of the limitations must be pointed out in the above project. As the material is adversely affected by cold weather, a shorter construction season is required. However, if this is observed, it is anticipated that no problems will occur due to frost damage.

Traffic cannot travel on the base course as quickly as with more conventional mixes due to the slower rate of strength gain. In critical cases, accelerators may be used to enhance the rate. One final limitation is the need for strict quality control of the mixing process and product.

Applicability to Ontario

The case history discussed above is extremely applicable to our Ontario ash utilization situation due to the similar climate of Pennsylvania and southern Ontario and similar ash characteristics exhibited in both regions.

As was indicated above, one major concern for use in cold weather climates is the length of the construction season which must be closely observed for a successful project to be realized.

Due to the variability of component characteristics, it is not recommended to simply use the mixture design developed for this project. Extensive testing must be undertaken to develop mixtures which are suitable for the local region of construction in southern Ontario. The above mentioned case history is meant to serve as a guide for similar projects elsewhere but modifications will be required based on the specific characteristics of the construction site in question (eg. climate, material properties).

4.3 Service Road, Pennsylvania

General Electric Company, Transportation Systems Divisions, operates a Power Station at Erie, Pennsylvania which serves as a supplier of heat, power and process steam and which in so doing produces three kinds of ash: fly ash, dry bottom and cyclone slag.

Concern for high maintenance costs of existing roads due to the rugged winter experienced has resulted in research developing low cost methods of road building. During construction of a new waste water treatment plant it was decided to construct the service road out of a fly ash/lime/boiler slag base which was mixed in the following manner by weight: 67% boiler slag, 29% fly ash and 4% lime/7/.

In this case history, mix-in-place procedures were utilized with the base area being trenched out and filled with slag which was spread with a dozer. Fly ash was then spread over the slag followed by the application of lime. The materials were mixed thoroughly and water added to make the mix plastic. In the contract, it was specified that the water application had to be controlled to prevent excessive concentration at the surface and that it should be gradually worked into the entire base course. The total allowable quantity of water to be added was not to exceed 15% by weight of the total mix.

The specifications again called for a compacted lift thickness of not less than eight inches (20 cm). Grading and rolling took place immediately after a uniform loose lift was achieved and good results were achieved using conventional road building equipment.

Compacted layers of the base course were then sealed to prevent loss of moisture using emulsified asphalt at a rate of 0.15 gallons/square yard. Specifications called for this to be applied no later than one day after final compaction which was then allowed to cure for at least 24 hours. A 2-inch layer of a bituminous wear surface was then applied to complete the road.

Immediately following the success achieved with the construction of this road, a second road intended for heavy duty tractor transport traffic was built.

The alterations from the previous design specifications were as follows:

A) Design Mix:

Boiler Slag - 60% by weight
Fly Ash - 35% by weight
Lime - 5% by weight

Again, the allowable quantity of water to be added was not to exceed 15% by weight of the total mix.

B) Compacted Lift Thickness:

This was increased from 8 inches (20 cm) to a minimum of 12 inches (30 cm) for the heavy duty road.

C) Surface Coating

2-1/2 inch (6.5 cm) - Bituminous wear surface
1-1/2 inch (3.8 cm) - Binder
1 inch (2.5 cm) - Top Coat.

It was reported that during construction of the heavy duty road, heavy rains hampered operations saturating the base course before the top course could be applied. Soft spots resulted which were, however, hardened and application of the top course followed.

Both roads have performed extremely well and although the company had some apprehension about what might happen when the frost went out in the spring, both roads made it through the winter in excellent shape.

One of the features which must be pointed out is that the road bases are 95% ash. This made the road far more economical than building with conventional materials. It should also be noted that although a mix-in-place operation was used here it was stressed that the ideal way to ensure a uniform consistent product would be to have plant-mix material. In this case, it was a question of economics.

Although LFA roads are not new, it was felt that this example, where boiler slag was substituted for the aggregate, made a significant contribution to the ash industry by introducing it in an area where it had not previously been promoted.

Applicability to Ontario

Due to the similar climates and ash characteristics, it is felt that this case history resembles what might be expected

from the construction of a base course of this sort in southern Ontario. However, it must be stressed that all fly ashes have different characteristics and that it will be required to prove that any mixture developed will work at a specific construction site even though the process would be duplicating what others have already done.

What this project demonstrates is the wide range of stabilizers which can be successfully utilized to establish a stable and durable road base. It also indicates that there is the possibility for a great deal of research work which could result in the removal of the label 'waste product' from ash and replace it with 'resource material'.

4.4 Airport Runway, Newark

During the 1960's, the Port Authority of New York and New Jersey made extensive use of lime-cement-fly ash (LCF) mixtures as a pavement material in the construction of runways or taxiways at Newark International and Kennedy International Airports. On the Newark site, it was reported that nearly two million tons (1.8 million tonnes) of LCF were used of which about 300,000 tons (270 000 tonnes) was fly ash/8/.

Preliminary work at the Newark site involved reclaiming the areas for development with hydraulic sand fill dredged from the sea. This was required as the sites native soil was meadow matt and marshland composed of decaying garbage having a thickness of 15 ft (4.6 m). A total of five feet (1.6 m) of sand was deposited as base and another layer was deposited for use as surcharge to achieve consolidation and to minimize in-service settlement.

Due to the proximity of fly ash, lime and cement sources, it was decided to utilize these materials as they were economically more feasible than conventional materials.

Fly ash sources were the Public Service Electric and Gas Company of New Jersey, the Metropolitan Edison Company of Pennsylvania and the New York State Electric and Gas Company in New York. The strength requirement of this mixture (LCF) measured after seven days at 130°F (54°C) was to be a minimum of 600 psi (4.1 MPa).

Conventional lime and cement types were used in the pozzolanic mixture. Coarse aggregate was used in certain areas and was specified as a crushed trap rock consisting of hard durable pieces with the following gradation: 100% by weight should pass through the 1.5 inch (3.8 cm) sieve, 60 to 90% through the 1 inch (2.5 cm) sieve and 0 to 15% through the 0.5 inch (1.3 cm)

sieve. Sand was also used in prescribed locations and it was required that not more than 10% of the sand should pass through the No. 200 sieve.

The base and subbase for runways, taxiways and apron areas were constructed with the typical cross-sections shown in Figure 2. Mix proportions used in construction are given in Table 6.

Quality control during the project was provided by the Port Authority of New York and New Jersey and is generally higher than achieved in normal highway pavement construction. Cores taken after one to two years in place reveal this fact as the compressive strengths are well in excess of the projected values of 2000 psi (14,000 kPa)/5/.

After five years of service, the only significant distress in the pavement was some shrinkage cracks in the shoulder area where an insufficient number of contraction joints was provided, and one crack which was thought to be the result of subgrade settlement in an area where an old drainage ditch existed prior to construction. It is felt that the pavements at Newark are smooth with a high serviceability rating and show excellent performance trends.

Two advantages which were highlighted in the report which dealt with this use of fly ash, were the enormous economic savings incurred. Typical material and installation costs for the LCF mixtures were $7.60 per square yard ($6.23 per square meter) compared to $12 for a conventional flexible pavement and $20 for a conventional rigid pavement structure. The second advantage was that the new pavement (LCF) was expected to gain in strength over a period of at least five years, thereby compensating for projected increases in aircraft sizes and weights.

Applicability to Ontario

Newark, being just outside of New York City has a very similar climate to that experienced in southern Ontario. As the coal is supplied from the same region of the United States as Ontario Hydro's coal, the fly ash possess similar characteristics in terms of free lime content, carbon content and pozzolanic reactivity.

Owing to the huge success of the project at Newark under the extremely intensive loadings of aircraft, the feasibility of utilizing a similar mixture of LCF exists in southern Ontario. As has been emphasized in previous case histories, the importance of a laboratory testing program and comprehensive quality control inspections is vital to the success of the final product. Final analysis of the above project revealed that the

minor cracking which did occur was a result of the jointing system used at the airport.

Contraction joints were placed at intervals of 150 ft to 200 ft (46-61 m). In some instances, the asphaltic concrete (AC) surface was partially sawed through, directly over the joints in the LFA base. However, in other cases no saw cuts were made and the AC was allowed to crack randomly. The sawed cracks were sealed immediately with a rubber asphalt filler while the random cracks were neglected allowing moisture to permeate into the LFA base course causing some distress due to frost. Obviously this is an improper construction technique which could be avoided in future projects in southern Ontario.

4.5 Warehouse Access Road, Ontario

The case histories studied up to this point have been located in the northern United States as lime-fly ash stabilized pavements have been studied extensively in these regions for the last 20 years. However, in September 1977, a fly ash-lime stabilized base course was constructed in Toronto, Ontario and served as a warehouse access road which is subjected to a high proportion of truck traffic/9/. The site was constructed after extensive laboratory work (compressive strength and freeze-thaw testing) was performed to develop a suitable mix design which would account for variations in the reactivity of the fly ash, quality of the aggregate and climatic conditions. Construction of a new road became necessary after the former unstabilized pavement failed after only five years of service.

The base course material of the new road is a blend of fly ash, lime and crushed stone. The fly ash was obtained from Ontario Hydro's Lakeview Generating Station and was found to have a carbon content of 9.2%. The lime used was a standard hydrated high-calcium product. The crushed stone aggregate used generally conformed to Class "A" granular base course as specified by the Ontario Ministry of Transportation and Communications. The fly ash and lime were mixed in a ratio of 3.8:1. The binder and aggregate were combined in a conventional concrete batch plant and water was added. The stabilized base course was delivered to the site in dump trucks. Varying binder contents of 36.5%, 20% 15% and 0% were used in four different road sections; A, B, C and D, respectively. The dimensions of the road was 200 m long and 6 m wide.

Construction procedures began by removing the failed existing pavement to a depth of 300 mm where a sandy silt till subgrade existed. This subgrade was tested, moistened with water and compacted before spreading the stabilized base course. As in the other case histories, conventional spreading equipment

(Jersey spreader) were used to ensure a uniformly thick base which upon compaction (using a 180 kN steel drum vibratory roller) had a thickness of 230 mm.

Sealing was accomplished using a tack coat of MC30 which was applied only hours after final compaction. The following day, a 75 mm surfacing of HL3 hot mix asphalt was spread and rolled. The road was then cured for three additional days bringing the entire construction time for the operation to six days.

It was found that Standard Proctor (ASTM D698-70) densities for the base course averaged 2024 kg/m^3 at 11.3% moisture content (see Figure 3).

During construction, compaction of the base course was monitored using nuclear density gauges. Section A was compacted to 82.9% and 93.8% of Standard Proctor which was significantly less than the specified 97% to 100% for a pozzolanic base course. This was due to the fact that the desired 12% moisture content from the batch plant was occasionally exceeded hampering compaction efforts. However Sections B and C had results ranging from 96.1% to 102.1% of Standard Proctor density. Section D was also well compacted.

Core samples obtained after construction revealed that the thicknesses of the base course and asphalt were as follows:

	Base Course (mm)	Pavement (mm)
Design Thickness	230	76
Actual Thickness		
Section A	222	111
Section B	241	61
Section C	231	58
Section D	N/A	N/A

Further monitoring was performed to ensure that adequate compressive strength was developed to resist freeze/thaw damage in the first winter. Highway agencies in the United States have established 2800 kPa as the minimum cured strength to resist frost damage. Due to a late start on constuction (September), it was felt that this was the field cured compressive strength entering the first winter and that possible frost damage might result. All compressive strength test results can be found in Table 7.

From this table, it is observed that the increase in compressive strengths after one year are a reflection of the binder content

in the road and that a strength gain was continuing in the second year of curing. Visual observation of the samples after one year indicated that Sections A and B had resisted the winter frost action. However Section C with less binder content showed evidence of some possible damage which could have been caused by road salts, poor mixing during construction or frost. Table 7 also indicates a dramatic loss of strength after 1-1/2 years in Section A which was felt to be due to binder defects of a nearly horizontal nature, possibly suggesting thermal stress.

Additional performance testing revealed that the expected life of the stabilized sections was 25 to 35 years as opposed to 5 years for Section D (unstabilized) of the road. It was stressed that this should be regarded with caution owing to the young life of the pavement. It was also determined that stabilized base course deflections were much less than those in the crushed stone section indicating that some distribution of the wheel load was occurring in the stabilized sections.

Observations of the stabilized base course in Toronto gives evidence that this material does perform well even under the harsh Canadian climate provided that the binder content is at least 20% of the mix by weight. Although some winter frost damage was experienced, performance measurements indicate a life span which is approximately four times that of conventional materials.

What was discovered was that thinner layers of stabilized ash and/or asphalt could have been used without appreciably affecting the experimental road performance. A reduction in pavement thickness from that used in the conventional road design was made possible due to the incorporation of binder.

As a result of the project, emphasis can be placed on the requirement to provide adequate curing time before the critical first winter freeze-thaw cycle (see Figure 4). It was recommended in the report that the lime-fly ash bases be placed no later in the year than the first week in September/9/. The extreme importance of quality control in the blending and spreading stage is emphasized, as possible problems with compacting to adequate densities could result. It is also recognized that extensive laboratory trials must be performed to take into account the locality of the construction site and the material properties of the mix constituents.

5.0 TECHNICAL FEASIBILITY IN SOUTHERN ONTARIO

As has been illustrated in the case history review in Section 4, there are a number of factors which ultimately affect the success or failure of a project.

The most important factor to be considered is the climate at the construction site location. As we live in a harsh climate, concerns about frost susceptibility are raised when dealing with fly ash due to its fine gradation and silt-like characteristics. For this reason, a mean daily temperature chart was established (see Table 8) to compare the climates of the case history regions studied with that of southern Ontario (Toronto). It can be seen from the chart that although the winter temperatures in these areas are slightly warmer than Toronto, the possibility for frost exists at all sites.

However, it was reported in the Harrison Power Station parking lot (cement and fly ash) that "no frost damage occurred even though the ambient air temperature had dropped below freezing several times during the first 90 days after completion".

The case in Shelock, Pennsylvania of the Ash Haul Road (lime + fly ash + aggregate) indicated that "the mix design chosen was satisfactory and should perform well under freeze-thaw conditions".

The case study in Toronto, Ontario of the warehouse access road (fly ash + lime + crushed stone) indicated that "the material does perform well even under the harsh Canadian climate provided that the binder content is at least 20% of the mix by weight".

Studies conducted by Ontario Hydro/10,11/ indicated that lime/bottom ash/fly ash mixes did not provide adequate test results when subjected to the freeze-thaw test. However, the validity of the tests conducted was subsequently questioned due to the realization that the strength gain for lime samples is much slower than for cement samples. Both types of mixes were tested after seven (7) days of curing. The results indicated that cement/fly ash/bottom ash mixtures were satisfactory while lime/fly ash/bottom ash failed.

As indicated in Section 3.1, testing on the lime mixtures should be conducted after a curing period of 28 days to obtain valid test results.

The case study in Erie, Pennsylvania of a service road (lime + fly ash + boiler slag) indicated that favourable results could be obtained and it was reported that the roads made it "through the winter months in excellent shape".

A further factor which should be emphasized is the need for an extensive laboratory testing program to establish satisfactory mixtures which will conform to strength and durability requirements as specified. The success enjoyed in each of the case histories was the result of determining an adequate

mixture, prior to constructing the base course. The mixtures chosen have been included to serve only as a guide for future projects. The use of fly ash as a base course material is feasible in southern Ontario if adequate testing is done on the mixtures as was indicated in Cragg's (1979) study/9/ of a LFA base course.

Additional concerns which must be addressed before beginning construction in southern Ontario of a fly ash base course include the quality of the aggregate, the carbon content and free lime content in the ash and the length of the construction season. It was recommended by Cragg/9/ that lime-fly ash bases be placed no later in the year than the first week in September allowing approximately three months of curing time before the expected first frost. It is suggested that this period could be reduced slightly in the case of cement-fly ash base courses owing to the more rapid strength gain experienced.

One primary concern which must be raised in any future application, is the concern for strict quality control of the fly ash and chemical additives, the mixing process and the spreading process. To ensure a good quality result, the fly ash properties must remain consistent and a consistent mix with accurate percentages by weight of each of the additives must be established. The thickness of the applied base course must be closely monitored and maintained as close as possible to the pavement design thickness.

Alterations in the fly ash properties must be addressed immediately and new mixtures must be established if it is determined that the changes which take place will adversely affect the performance of the final base course. As we are primarily dealing with a Class F fly ash similar to that produced in the north-eastern United States, it is expected that similar strength and durability characteristics to those experienced in each of the case histories will result and that with an effective quality monitoring program, the use of fly ash as a base course in southern Ontario is technically and practically feasible.

6.0 SUMMARY

It is concluded, based on past experience and techniques, that the use of fly ash in combination with chemical additives such as lime or cement is a technically feasible alternative for the construction of highway and road base courses even though the climate of southern Ontario presents some problems when dealing with frost susceptibility. It is felt that these problems can be overcome with the addition of lime or cement in quantities which exceed 20% by weight of the mixture/9/ and if adequate

curing time is provided to allow strength gain in the base course before the first expected frost.

Although these conclusions are based on past experiences, both laboratory testing and field testing indicate that fly ash mixture in correct proportions as determined by standard durability and strength tests will provide a suitable base or subbase course which is non-frost susceptible, and of sufficient strength to meet design criteria/11/.

In utilizing fly ash in the above-mentioned manner, there are a number of beneficial effects which will be experienced by power generating utilities:

1. Reduce the existing stockpiles of fly ash.

2. Utilize the fly ash currently being produced by these thermal generating stations thereby eliminating disposal costs.

3. A reduction in consumer reluctance to accept coal ash as a resource as opposed to simply a waste material.

A further advantage is the economic savings which municipalities and governments will experience. This subject has been avoided as the local characteristics of a particular job site will greatly influence the exact cost for that project. These include among others the haul distance from a fly ash source, the amount of fly ash required and the amount of chemical additives required to produce a suitable mixture, an analysis which extends beyond the scope of this project. It is suffice to say that, in areas where conventional materials have limited availability or are economically unfeasible, fly ash may be successfully used as a substitute with no adverse performance characteristics.

Based on the work conducted in the preparation of this report, the following recommendations are made:

1. Fly ash base course mixtures be utilized in test sections of highways and roads by the Ontario Ministry of Transportation and Communications and that strict quality control be emphasized during construction and field monitoring procedures.

2. The chemical processes involved in mixing lime, fly ash and cement should be studied and well documented to establish limits and design criteria which will be directly applicable to southern Ontario as opposed to relying on standards established in the United States.

3. The long term performance of this innovative paving system be closely monitored and documented. Factors of concern include leachate migration, fatigue life of the pavement and the effects of deleterious substances that may degrade the material or cause an alteration in the physical and chemical properties experienced in the pavement cross-section.

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TABLE 1

Properties of High Calcium Hydrated Limes

Constituent	% by Weight
CaO	92.25 to 98.00
MgO	0.30 to 2.50
CO_2	0.40 to 1.50
SiO_2	0.20 to 1.50
Fe_2O_3	0.10 to 0.40
Al_2O_3	0.10 to 0.50
H_2O	0.10 to 0.90
Specific Gravity	3.2 to 3.40

Source : Cautillo, M. 1978 . Use of lime and cement stabilized coal ash as highway subbase. B.A.Sc. thesis. Dept. of Civil Engineering. University of Toronto. Toronto, Ontario.

TABLE 2

Oxide Composition of Normal Portland Cement

Oxide	Range, % by Weight
Lime, CaO	60 - 66
Silica, SiO_2	19 - 25
Alumina, Al_2O_3	3 - 8
Iron, Fe_2O_3	1 - 5
Magnesia, MgO	0 - 5
Sulfur Trioxide, SO_3	1 - 3

Source : Same as TABLE 1/.

TABLE 3

STONE AGGREGATE GRADATION

SIEVE SIZE	PERCENT PASSING
2"	100
3/4"	70-100
3/8"	58-100
#4	45-80
#16	25-50
#100	6-20

TABLE 4

OPTIMUM PERCENT OF FINES
MIX DESIGNS

COMPOSITION OF MIX - % BY WEIGHT		MAXIMUM DRY DENSITY	OPTIMUM MOISTURE CONTENT
FLY ASH	AGGREGATE	(PCF)	(%)
12.5	87.5	138.2	6.1
15.0	85.0	138.7	6.1
17.5	82.5	135.8	6.2

TABLE 5

Optimum Mix Design

Mix Composition (% By Weight)			Maximum Dry Density (pcf)	Moisture Content (%)	7 Day Strength (psi)
Lime	Fly Ash	Aggregate			
3.0	12.0	85	136.3	5.7	1815
3.5	11.5	85	138.1	6.1	1927
4.0	11.0	85	137.1	5.2	1453

(Source of Table 3, 4, and 5: Novotny, S.J. 1985. Fly Ash/Lime/Aggregate Roadway Base Course for Keystone Steam Generating Station Ash Haul Road.)

TABLE 6

Approximate Mix Proportions Used in the Newark Airport Pavement

Mix Designation	Incredients, %				
	Lime	Cement	Fly Ash	Sand	Stone
A	3.6	0.9	12	53.5	30
B	3.2	0.8	14	82	0
C	2.8	0.7	14	82.5	0

TABLE 7

COMPRESSIVE STRENGTH OF STABILIZED BASE COURSE

Sample Age	Average Compressive Strength (kPa) Section A	Section B	Section C	Sample Type
28 days	-	1 700	2 600	field cylinder*
90 days	11 700	6 250	6 100	field cylinder*
1 year	16 000	15 700	9 900	76 mm diameter core
2 years	7 600	15 950	12 100	76 mm diameter core

*150 mm diameter x 300 mm compacted cylinder field samples were laboratory cured.

(Source: Cragg, C.B.H. 1979 . Field Performance of a Lime-fly Ash Stabilized Base Course. Paper presented to the 1979 Roads and Transportation Association of Canada Conference, Regina, Sask.

TABLE 8

CLIMATIC COMPARISON

MEAN DAILY TEMPERATURES [°C]

MONTH	TORONTO	ERIE(PA.)	NEWARK(N.J.)	SHELOCTA(PA.)	HAYWOOD(W
J	-4.6	-2.6	-0.3	-1.2	0.6
F	-3.9	-3.1	0.3	-0.6	0.4
M	0.7	0.9	4.8	3.8	4.6
A	7.6	7.5	10.9	10.1	10.6
M	13.6	13.6	16.6	16.1	16.4
J	19.1	19.3	21.9	21.1	21.4
J	22.0	21.7	24.7	23.8	23.1
A	21.2	21.0	23.7	22.7	22.2
S	17.1	17.4	19.9	18.6	18.5
O	11.0	11.4	14.2	12.4	12.1
N	4.9	5.1	7.9	5.5	5.2
D	-1.6	-0.7	1.4	-0.2	0.6
AVG.	8.6	9.3	12.1	10.6	10.0

Source:

Toronto Data: Canadian Climate Program. 1982 . Temperature : 1951-1980 . Vol.2, p.97. Environment Canada. Ottawa, Canada.

Erie Data: Climates of the States. 1978. Vol. 2.p. 842. Gale Research Company. Detroit, Michigan.

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Shelocta Data: Same as Erie. p.841.

Haywood Data: Same as Erie. p.1080.

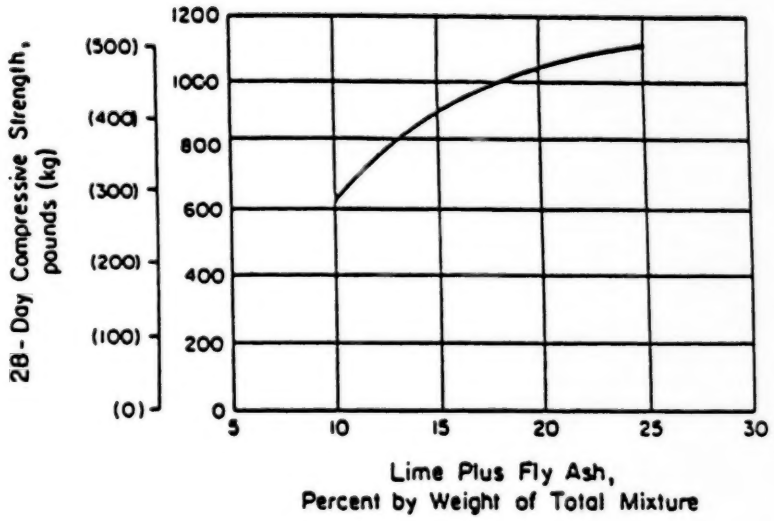

FIGURE 1

VARIATION OF 28-DAY COMPRESSIVE STRENGTH WITH LIME PLUS FLY ASH CONTENT (STRENGTH IS EXPRESSED AS TOTAL LOAD)

Source: Dry Ash Utilization Manual. 1985. Project 2422-2 Prepared by GAI Consultants Inc. Monroeville, Pennsylvania.

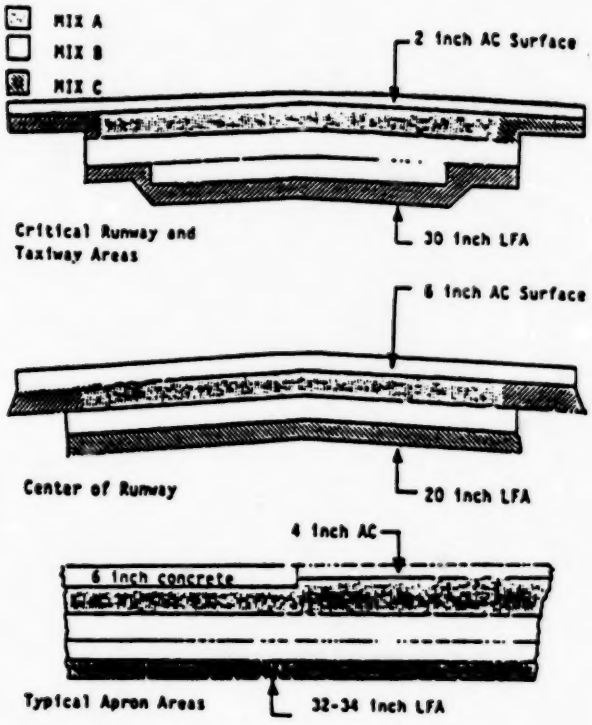

FIGURE 2

TYPICAL CROSS SECTIONS USED AT NEWARK AIRPORT

Source: Transportation Research Board. 1976.
Lime-Fly Ash-Stabilized Bases And Subbases.
National Research Council. Washington, D.C.

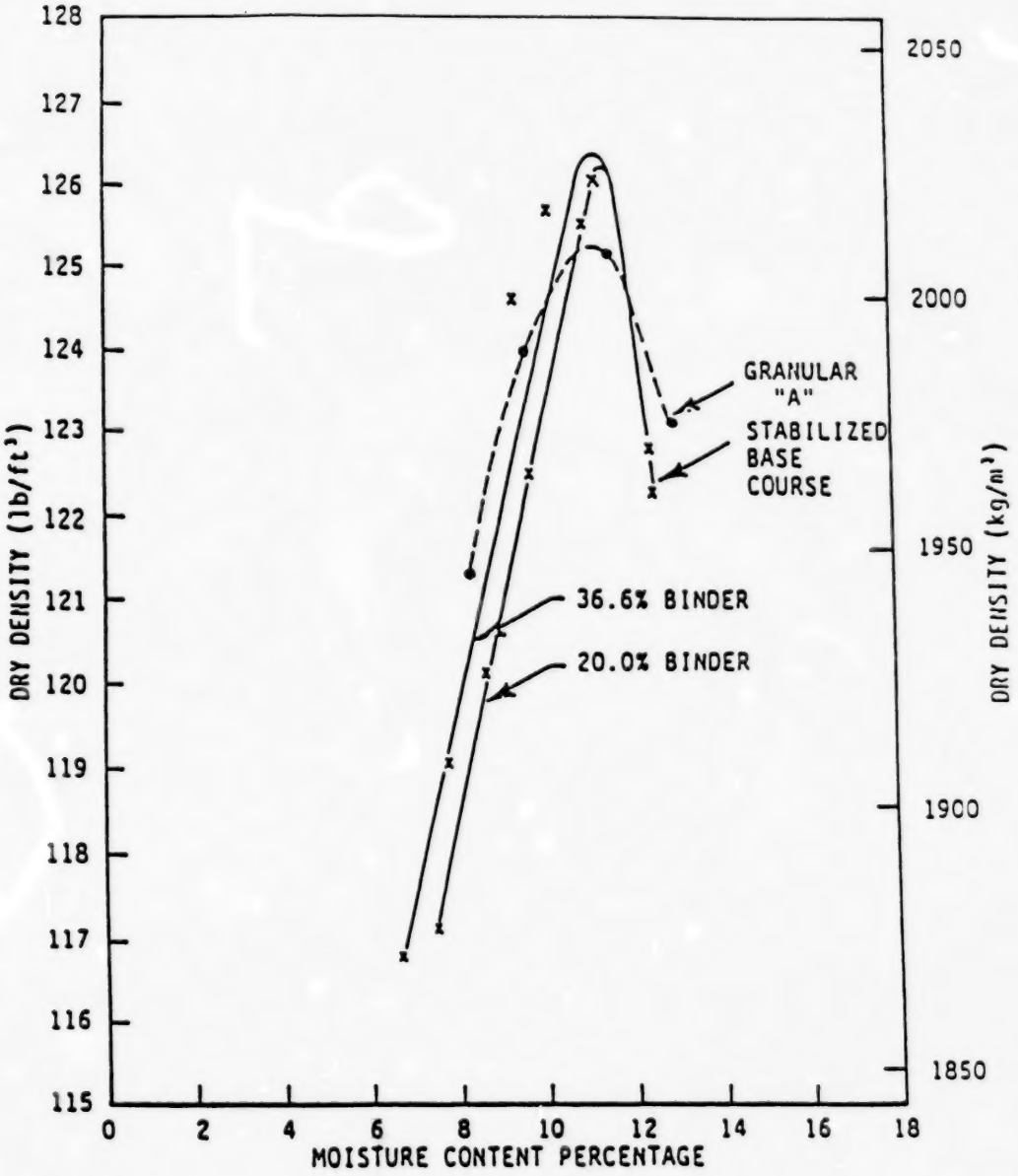

FIGURE 3

STANDARD PROCTOR TESTS ON STABILIZED BASE COURSE

Source: Cragg, C.B.H. 1979.
Field Performance Of A Lime-Fly Ash Stabilized Base Course. Paper Presented To The 1979 Roads And Transportation Association Of Canada Conference, Regina, Sask.

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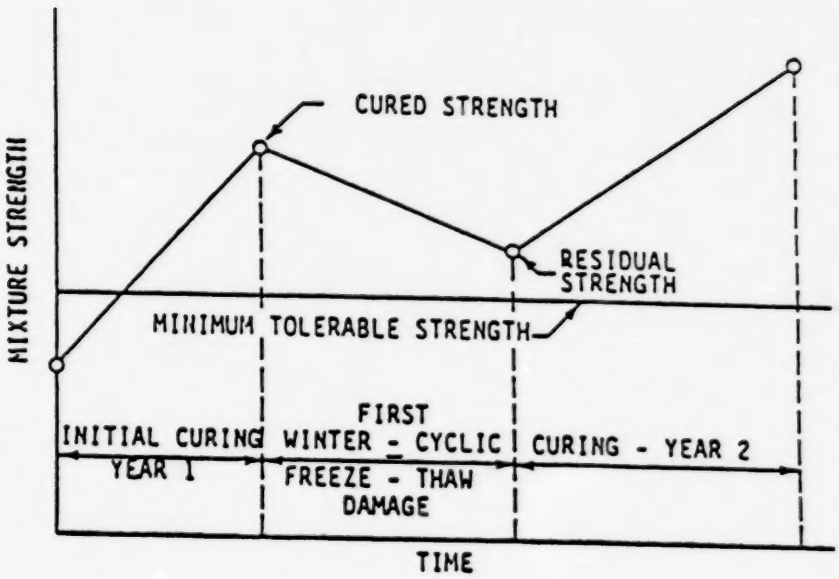

FIGURE 4

THE RESIDUAL STRENGTH CONCEPT OF FREEZE-THAW DURABILITY

Source: Cragg, C.B.H. 1979.
Field Performance Of A Lime-Fly Ash Stabilized Base Course.
Paper Presented To The 1979 Roads And Transportation Association Of Canada Conference, Regina, Sask.

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